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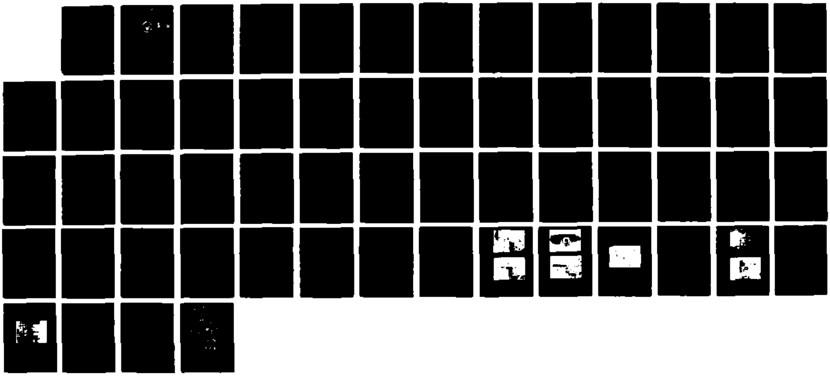

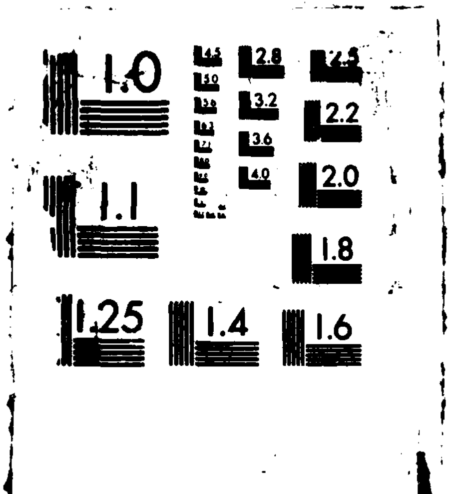

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A HOLOGRAPHIC INVESTIGATION OF PARTICULATES IN METALLIZED SOLID FUEL RAMJET COMBUSTION

by

Crawford A. Easterling III

September 1987

Thesis Advisor: David W. Netzer

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A Holographic Investigation of Particulates
in Metallized Solid Fuel Ramjet Combustion

by

Crawford Alan Easterling III
Lieutenant, United States Navy
B.S.M.E., United States Naval Academy, 1980

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

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ABSTRACT

An investigation was conducted pursuant to the development of a holographic technique to be used in the study of particulates in metallized solid fuel ramjet combustion. Additionally, a technique for generating a time-space dependent temperature profile of a two-dimensional solid fuel ramjet fuel slab, was developed. A holocamera was designed and constructed for use with a two-dimensional solid fuel ramjet. Eleven micron resolution was obtained using diffuse illumination. Initial attempts to obtain holograms of metallized fuel combustion were unsuccessful. The fuels tested either would not sustain, or, produced copious amounts of smoke which precluded a sufficiently intense scene beam from reaching the holographic plate. Use of .005 inch diameter, Chromel-Alumel thermocouples, imbedded at measured depths in the fuel slab, provided subsurface temperature data as a function of time and location, until exposed to free stream conditions.

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I would like to express my sincere appreciation to Professor David W. Netzer for his assistance and guidance in the completion of this project. Special thanks to Alon Gany for his comments on boron combustion. Also deserving of mention is Mr. Pat Hickey, for help in the design of the holocamera, Mr. Don Harvey, who contributed his years of experience to the construction of the holocamera, and Mr. Harry Conner, for his common sense.

I. INTRODUCTION

In both principle of operation and simplicity of design, the ramjet offers a method of propulsion superior to any other chemical propulsion system for advanced, long-range tactical missile applications. Historically, ramjets for tactical applications have not been developed for two reasons. First, solid propellant rockets have been able to meet the requirements of previous tactical systems. Secondly, despite the fact that the ramjet does not need to carry its own oxidizer, as does the solid rocket, it must be boosted to a supersonic velocity in order to operate. However, with the emergence of the integral rocket ramjet, an arrangement which combines the boost function of the rocket with the supersonic cruise efficiency of the ramjet, interest in the ramjet has been revived.

Current requirements for advanced tactical missiles mandate a propulsive system which can offer enhanced range and high speed at a wide range of altitudes, and allow the vehicle to remain in a powered state to target impact. Add to these needs the desire for a weapon of minimum volume and cost, and the integral rocket ramjet becomes a viable solution. As seen in Figure 1.1, the ramjet is capable of operating over a range of Mach numbers from 0.8 to 5.0 and altitudes ranging from sea level to 100,000 ft. Above Mach

1.5, the fuel specific impulse of the ramjet becomes competitive with other airbreathing engines, while above Mach 2.0, the ramjet generally has a thrust to weight ratio in excess that of turbojets or sustainer rockets. [Ref. 1]

In an effort to optimize the performance of the ramjet a wide variety of fuels, both solid and liquid, have been investigated. Analysis and experimental evidence indicate that the solid fuel ramjet has good potential for tactical applications, while maintaining a relatively simple design.

The combustion of solid hydrocarbon fuels has been studied extensively. Polymers such as hydroxy-terminated polybutadiene (HTPB) and polymethylmetacrylate (PMM - Plexiglas) are common examples of such fuels. However, higher energy density fuels are also being considered. Metals, in principle, can provide this increased theoretical performance. Thus, elements such as boron, aluminum, lithium, magnesium, titanium, and carbon are being investigated. Boron, with a 30% higher energy per unit mass and a 300% higher energy density than most hydrocarbon fuels, is receiving considerable attention.

To use only boron as a fuel would be impractical due to fabrication, as well as combustion considerations. Therefore, boron is usually found in the form of a powdered metal suspended within a hydrocarbon matrix, which both enhances combustion efficiency and improves material properties. In order to further enhance the combustion

efficiency of boron, small amounts of more easily ignited metals (such as magnesium) or oxidizer (such as teflon) may be employed.

The combustion characteristics of hydrocarbon fuels are well understood and are quite accurately modeled by semi-empirical regression rate and combustion efficiency correlations. On the other hand, insufficient research has been conducted into the combustion process of highly metallized fuels. While some modeling of boron combustion has been attempted, accurate data required to verify or improve the accuracy of these models is lacking. Regression rate and combustion efficiency correlations need to be further developed and validated.

Boron is difficult to burn in that it ignites at a very high temperature. Frequently, the combustion time required by the boron particles exceeds the residence time of the particles within the combustor. The ejection of these unburned particles (10 to 30% of the exhaust can be condensed phase) may cause two phase flow losses to become significant, and certainly the lost energy in the unburned boron particles is significant. Unfortunately, the combustion environment within the ramjet is exceedingly hostile to most forms of measurement, and attempts to record the combustion event are difficult at best. To a certain extent, high speed motion pictures have captured metallized fuel combustion, but they are unable to record a

representative sample of the condensed phase. The purpose of this investigation was to use holographic techniques to record a volumetric sample of condensed phase within the ramjet combustor for a variety of metalized fuels, and ranges of air mass flux and combustor pressure. Furthermore, attempts were made to obtain a temperature profile of the solid fuel slab as a function of space and time, in hopes that it might be possible to find a correlation between subsurface temperature and the ejection event of metal flakes and agglomerates from the fuel surface.

II. BACKGROUND

A. RAMJET PRINCIPLE OF OPERATION

The basic ramjet engine employs no moving parts, making it capable of a level of simplicity impossible to achieve in other airbreathing engines. Principle ramjet components include a diffuser, a fuel injection system (liquid fueled ramjets only), a combustor, and an exhaust nozzle. Due to this simplicity, the ramjet design may be quite light and able to achieve speeds up to Mach 5.0 or 6.0 where dissociation effects make higher velocities impractical.

In order to initiate operation, the ramjet must first be boosted by external means to a minimum velocity of Mach 1.5. At this speed, air is admitted to the engine through the diffuser, where the kinetic energy of the flow is converted into enthalpy through adiabatic compression. This results in a high pressure and temperature, subsonic flow through the combustor. The diffuser typically slows the free stream air to this subsonic state via a series of oblique shocks followed by a single normal shock. The air is then mixed with fuel either through a liquid fuel injection system or through vaporization of a solid fuel, thereby increasing the mass flow approximately 5 to 10%. The gaseous mixture is ignited in an ignition sequence and then becomes self-sustaining. The thermal energy of the combustion products

is then converted to kinetic energy as the flow passes through the exhaust nozzle.

B. COMBUSTION CHARACTERISTICS OF THE SOLID FUEL RAMJET

A standard combustor configuration for the solid fuel ramjet is shown in Figure 2.1. It includes a rearward facing step at the head end air inlet, a main combustor section where the fuel grain is located and an aft mixing section.

As might be expected, the solid fuel ramjet combustor must provide a flame stabilization device for sustained combustion. In the configuration shown, this is accomplished by a sudden expansion at the rearward facing step, which forms a recirculative zone for a fuel rich, air -fuel mixture. The heat generated by the combustion of this mixture allows a flame to be sustained in the developing boundary layer region downstream of flow reattachment.

The recirculation zone terminates at an unsteady reattachment point on the fuel grain, at a distance approxiamtely 7 to 8 step heights from the step. Downstream of this point, a boundary layer flow develops. This flow is fuel rich near the surface, while the adjacent centerline flow is oxidizer rich. The result is a turbulent diffusion flame at the interface between the two zones, which may be characterized as a narrow flame sheet close to the fuel grain surface. Just prior to the aft mixing zone, an aft

orifice plate may be installed to enhance the mixing of the fuel-air mixture in the aft mixing zone, and thus insure complete reaction between the oxygen and vaporized fuel.

C. METALLIZED FUELS

1. High Energetic Performance Fuels

As was mentioned previously, most solid fuel ramjets have depended upon hydrocarbons as a principle source of fuel. However, other fuels are available which have higher heats of combustion. In particular, metals promise to deliver a higher energetic performance than the traditional hydrocarbons.

The energetic performance of an air breathing engine is often evaluated in terms of its specific impulse, I_{sp} and thrust specific fuel consumption, TSFC. Combustor performance is sometimes more conveniently discussed in terms of static specific impulse, $I_{sp,s}$. It can be shown [Ref. 2] that the heat release per unit mass of fuel, q_R, is linearly proportional to the static specific impulse,

$$I_{sp,s} \sim q_R$$

Also

$$q_R = -\Delta H^{\circ}_R$$

where $-\Delta H^{\circ}_R$ is the heat of combustion for a complete reaction with gaseous oxygen. The negative sign designates an exothermic reaction. For theoretical performance, the entire heat of combustion is considered to be released in

the combustion chamber. This being the case, it would seem obvious to search for fuels with the highest possible values of q_R. However, an additional constraint applies. In most cases a ramjet is volumetrically limited, thus restricting the total amount of fuel which may be packaged. This suggests that energy density, the product of density and q_R, should be used as the criterion for fuel selection.

The search for elements with a high heat of combustion per unit mass and unit volume yields Figure 2.2 [Ref. 2]. It is seen that hydrogen has a heat of combustion of -28.9 kcal/gm, nearly twice that of the next highest value of -15.88 kcal/gm for beryllium. However, besides the fact that it has a negligible energy density, gaseous hydrogen has no application in a solid fuel propulsion device. On the other hand, beryllium, which does have a very high energy density, is unfortunately also quite toxic. The remaining promising elements include boron, magnesium, aluminum, silicon, vanadium, lithium, titanium zirconium and scandium. Of these possibilities, lithium is a serious fire hazard, scandium is very rare and expensive, silicon and vanadium pose health risks and zirconium tends to ignite spontaneously. Of the remaining metals, the most practical for solid fuel ramjet application are boron, magnesium and aluminum. Boron is an outstanding energetic performer with an energy density of -33.19 kcal/gm followed by aluminum at -20.01 kcal/gm and magnesium at -10.28 kcal/gm [Ref. 2].

Gany and Netzer [Ref. 2] discuss another possible source of energetic fuel; the metal hydride which, by virtue of the hydrogen present in its molecule, has a higher heat of combustion than its elemental metal. Unfortunately, the metal hydrides are very light and TiH_2, with the greatest energy density of the group at -19.92 kcal/cc cannot compete with boron. Besides, TiH_2 decomposes at 400 C. Borides and metal-metal compounds also demonstrate potential as energetic fuels and AlB_{12} has a heat of combustion per unit mass greater even than that of boron. Another attractive candidate is boron carbide, B_4C, the cheapest source of boron.

2. <u>Metallized Fuel Combustion Characteristics</u>

As spectacular as the theoretical energetic performance of boron is, heat of combustion per unit mass is not the only factor requiring consideration in the selection of a solid fuel. Ignition and combustion characteristics have a significant impact on combustion efficiency and are, therefore of prime concern in fuel selection. In the past, boron has displayed a number of troublesome ignition and combustion traits.

The boron combustion process is not completely understood but it has been modeled with some success. One model [Ref. 3] is summarized below. A Boron particle, upon being ejected from the solid fuel surface, is coated with a solid boron oxide coating of approximately 10 Å thickness.

solid boron oxide coating of approximately 10 Å thickness. The boron oxide has a melting point of 720 K, while the boron itself melts at 2450 K. After ejection, the particle burns in two stages. In the first stage (ignition stage), heat transfer from the gas flow cause the oxide layer to melt, permitting the boron and oxygen to diffuse and react, the reaction rate increasing as the temperature increases. As a result, the particle becomes luminous. The particle begins to glow and then extinguishs as the oxide layer thickens with increased oxygen diffusion, thus causing the diffusion between reactants to slow. If the particle is exposed to a further increase in temperature, the volatility of the oxide increases and the rate at which the boron and oxygen diffuse and react exceeds the rate at which the oxide forms, and the oxide quickly evaporates. At this point the particle reignites in a brighter flame and can continue to burn until combustion is complete, assuming sufficient oxygen is made available.

Boron particle loading in a solid fuel ramjet may approach 70%. Additionally, boron particles on the order of 1.0 micron may be required in order to insure complete combustion within a practical residence time. When a high concentration of small boron particles is burned with its binder, some of the metal is no longer ejected as single born particles but, rather as coalesced agglomerates of varied size. Control over combustion time is lost as the

agglomerates have different ignition properties than the single particles. The ignition temperature for the agglomerate may be as much as 900 K lower than that of the particle. This is advantageous, but these particles require longer burn times, thus requiring longer residence times to insure complete combustion. If the agglomerates pass through the ramjet unburned, obvious thermal inefficiencies and two phase flow losses will result.

A number of factors affect the combustion of the boron once it has been ejected from the fuel surface. Gas temperature, oxygen concentration, oxide formation rate, reactant diffusion rates, particle trajectory after ejection, ejection angle and velocity and motor air mass flux. For example, if a particle ejection velocity and trajectory place it in the diffusion flame where temperatures are high, a short ignition time will result. If the ejection velocity is to high, the particle may pass through this zone without igniting and exit the motor. If the velocity is much lower, the particle will remain in the low temperature boundary layer flow and exhibit a long ignition time. According to Gany [Ref. 4], even very small particles may need as much as 1 meter for complete combustion. Particles seem to ignite best were the oxygen concentration is low while sustained combustion is encouraged by oxygen rich zones. Gany notes that even particles of a 50 micron diameter will burn completely in

the oxygen rich centerline region of the combustor, while the same particle, if ignited, would burn poorly near the fuel surface. [Ref. 4]

The conditions for ignition and combustion are obviously contrary, but if a way can be found to ignite the particle in an oxygen lean, high temperature environment, and then sustain combustion in an oxygen rich zone, high combustion efficiencies can be attained. Gany observes that the ignition stage may be expedited by preheating at the fuel surface. Fuels composed of a boron-magnesium-teflon mix attempt to do just that. The magnesium raises the temperature of the boron at the surface, while the flourine of the teflon provides an additional oxidizer source to enhance combustion.

With the exception of some preliminary work using high speed motion picture cameras by Netzer and Gany, almost no research into the behavior of boron particles in the SFRJ combustor has been reported. In order to study particle and agglomerate behavior and size, however, some method of recording the combustion process is required. High speed film has demonstrated insufficient resolution, and cannot record a representative volume. The solution attempted here makes use of holographic techniques to capture a volume of particles in the boundary layer region of the main combustor.

D. HOLOGRAPHY

Conventional photography depends only on light intensity to produce two dimensional photographic images. Exposed photographic film responds to light intensity such that when developed, the film density is proportional to the amplitude squared of the light to which it was exposed. The image produced is completely independent of the phase of the source light. A three dimensional effect may only be suggested in a photograph through creative lighting techniques. There is no way for a photograph to store phase information from the illuminating wavefront. The hologram however, is capable of storing both the amplitude and phase information from an illuminating source, thus making it possible to record a three dimensional image. All that is required is a coherent light beam from a laser and the ability to split that beam to form a reference beam and a scene or object beam. The scene beam illuminates the object to be photographed while the reference beam passes undisturbed. When the two beams are recombined an intereference pattern is formed which is representative of the object. The amplitude and phase of this pattern is then recorded on the photographic plate, thus forming a hologram. [Ref. 5]

A schematic of a simple holocamera is shown in Figure 2.3. Its principle components are the laser light source, a beam splitter, beam directing mirrors and a photographic

plate. The beam emitted from the laser passes through the beam splitter such that the scene beam continues undeflected to its target object, while the reference beam departs the beam splitter at an angle and an intensity dependent upon the beam splitter angle of incidence. After illuminating the target object, the scene beam and the reference beam are recombined at the photographic plate, thus recording the object image as described above.

The only requirements on beam geometry are that the scene-reference beam paths be equalized to minimize temporal coherence requirements, and that spatial alignment of the two beams is assured. Factors affecting the quality or resolution of the hologram produced are the ratio of reference beam to scene beam intensity at recording, light intensity versus exposure time, spatial resolution and equipment isolation from vibration (stability). The hologram is reconstructed by illuminating the interference pattern with a laser light source of an identical or nearly the same wavelength (the identical wavelength will yield better resolution). The result is a three dimensional image reconstructed in space which is nearly indiscernable from the original target object. Any plane of this image may then be recorded using conventional still photography or video for further data reduction.

E. AUTOMATIC DATA RETRIEVAL FROM SFRJ HOLOGRAMS

Given that an acceptable hologram of the combustion process has been recorded, the raw data must be gathered from the hologram and reduced before it can yield any useful information. While it is possible to manually determine particle diameters and calculate size distributions, the work is tedious and time consuming. Any method which could introduce some degree of automation to the process would be desireable. As it happens, Professor J. P. Powers of the Naval Postgraduate school has developed, with the assitance of others [Ref. 6], such a technique. Through computer processing of the holographic image, it is possible to measure particle sizes and produce a particle size histogram. After a hologram has been developed, the reconstucted image is recorded and digitized for storage on an IBM PC/AT. Speckle reduction filtering and an application of image thresholding are used to isolate actual particles from noise. Feature identification connects feature pixels for recognition as a single object. These feature are then sized for area, roundness and centroid location and a size distribution histogram is produced. By using a geometric speckle reduction filter, a resolution of about 14 microns has been achieved.

III. DESCRIPTION OF APPARATUS

The principle components of the experimental apparatus included a two dimensional solid fuel ramjet with a vitiated air heater, an igniter, a purge gas system, a computer controlled test sequence, an acquisition and reduction system, a lens-assisted, reverse reference beam holocamera, and a one joule, Q-switched pulsed ruby laser light source.

A. TWO-DIMENSIONAL SOLID FUEL RAMJET MOTOR

The solid fuel ramjet motor was comprised of four primary sections [Ref. 7]:

1. The head end with a variable throat area inlet and rearward facing step
2. The main combustor
3. The aft mixing section
4. The exhaust nozzle

The head end was designed to receive its air supply from the vitiated air heater. The heated air first passed through a flow straightener, and then through a variable inlet step height apparatus, which permitted step height to be selected over a range of values. Step height could be preset or varied during motor operation from a remote control (Figure 3.1).

The main combustor interior dimensions were 2.5 inches in width by 1.5 inches in height and 16 inches in length. Solid fuel slabs were precut and cemented to the top and bottom of the motor. The fuel slabs were 2.5 inches in width with an average thickness of 0.25 inches, making the port height 1.0 inches. On one side of the motor, three windows were provided for high speed motion pictures at the reattachment point, mid-chamber and the boundary layer combustion region prior to the aft mixing zone. On the other side of the motor a fourth window was installed, opposite the window at the boundary layer combustion point, in order to permit the laser beam to pass completely through the combustion zone (Figure 3.2). For tests, the remaining two windows were fitted with blank-off plates. The viewing ports were constructed of 0.25 inch thick Plexiglas windows with an air injection purge system and metal shields which partially covered the windows (Figure 3.3). This arrangement prevented the windows from fowling and burning when exposed to the combustion process. The air purge fed 500 psia air from a supply bottle to the window via a remotely controlled valve. The air passed through a sintered ring between the window and a 1.5 inch diameter steel plug. The plug had a 0.5 inch diameter hole drilled through it to permit passage of the laser beam. Experience during previous experiments has shown that the purge air mass flow rate selection is of critical importance in

keeping the window clear without affecting the combustion process.

The aft mixing chamber was located immediately aft of the fuel slabs. It had dimensions of 2.5 inches in width by 1.25 inches in height and 6 inches in length. In this region the fuel-air mixture was able to burn more completely due to increased residence time and mixing.

A converging exhaust nozzle was located at the exit from the aft mixing chamber. A number of different diameter carbon nozzles were available for the control of combustion chamber pressure. This investigation utilized only the 0.75 inch diameter nozzle, due to the high chamber pressure required for efficient metallized fuel combustion.

B. VITIATED AIR HEATER

Actual flight condition enthalpies were simulated by using a 3000 psi air supply with a vitiated air heater fueled by gaseous methane. Oxygen was supplied to replace that consumed in the heater combustion process. The system was capable of supplying mass flow rates of up to 2.5 lbm/sec and temperatures up to 1500 R. Heater output was fed directly to the ramjet air inlet and was regulated through a sonically choked converging nozzle. Pressure and temperature were measured at the sonic choke and used to determine mass flow rate by conservation of mass applied to a choked flow.

C. IGNITERS

Solid fuel ignition in the combustor was achieved with two ethylene-oxygen torches which were directed into the recirculation zone and across the fuel slabs (Figure 3.4). Additional ethylene was injected into the recirculation zone from the base of the inlet steps to promote ignition. Ignition gas mass flow rates were controlled by again using a sonic choke at a set pressure. Once ignition was achieved, the torches and supplemental ethylene were secured and the motor became self-sustaining.

D. PURGE SYSTEM

Upon completion of a desired run period, the air flow upstream of the combustor was automatically dumped, and nitrogen or argon gas was fed through the motor for approximately 4 seconds to ensure that all combustion was extinguished.

E. DATA ACQUISITION SYSTEM

A 3054A computer based Hewlett-Packard data acquisition and control system was used for experimental data acquisition. Principle componets were a HP-9836 computer, a 3497A data acquisition and control unit, and two A/D integrating voltmeters (HP-3456A and HP-3437A).

The system measured pressures at the air sonic choke, the combustor chamber, the air heater fuel and oxygen chokes and the ignition gas fuel choke. All mass flow rates were

set through computer entry prior to a test by setting the correct pressures. Air, air heater fuel, air heater oxygen and ignition fuel mass flowrates were all controlled with this method. Upon completion of a test, reduced data output provided the following as a function of time:

a. air mass flowrate

b. air heater fuel mass flow rate

c. air heater oxygen mass flow rate

d. SFRJ ignition fuel mass flow rate

e. Temperature at SFRJ motor air inlet

f. SFRJ chamber pressure

g. SFRJ head end pressure

h. Temperature at the air sonic choke.

F. REMOTE CONTROL PANEL

All manually controlled functions were operated from a control panel remotely located in the control room. The control panel permitted the operator to initiate vitiated air heater operation and supply air flow through the motor. Window purge was also manually operated. Once air flow was initiated, the computer control system took over, completed and terminated the test.

G. RUBY LASER HOLOGRAPHIC ILLUMINATOR

The laser illuminator consisted of a Kerr cell Q-switched oscillator with a 0.03 percent ruby rod. The output of the rod was expanded and collimated. Emission was

1-3 joules for approximately 50 nanosecond duration of 0.6943 micron wavelength light. All laser optics were contained in a common chest with a dark field autocollimator. For the purpose of laser alignment, a helium-neon gas laser was included in the cabinet. The beam of the helium-neon laser could be superimposed onto the ruby laser beam. [Ref. 8]

H. HOLOCAMERA

A lens assisted reverse reference beam holocamera, based on an exisiting AFRPL holocamera design [Ref. 9], was designed and constructed specifically for this investigation (Figure 3.5). For simplicity, the holocamera was built around the removable lens-plate box and shutter electronics used in the AFRPL holocamera.

The camera principle of operation was relatively simple. A collimated beam from the illuminating pulsed ruby laser passed through the camera port and was immediately turned 90 degrees by a dielectric mirror. The next optical element encountered was a wedge beam splitter which reflected 15% of the beam from its upper surface and 13% from its lower surface into the reference beam channel. The remaining 72% of the light passed through the beam splitter and into the scene beam channel. The transmitted scene beam was then directed by two dielectric-coated mirrors through a pair of collimating lenses which invert the beam through a small

aperature. The inversion process was required for spatial matching. The scene beam then exited the main beam splitter box via an opal glass diffuser, which was mounted on the final inverting lens.

Next, the collimated scene beam passed through the scene volume. Located in the scene volume was the solid fuel ramjet. The beam passed through the combustor window, then through the combustor volume and exited through the opposite window. The beam then entered the removable lens-plate box.

The lens-plate box consisted of two assisting lenses, optical filters, a Uniblitz shutter mounted on a removable plate, the hologram mounted kinetically on a brass holder and two aluminized front surface mirrors. The lenses were used to enhance the high resolution of the camera, while the filters excluded the flame light while passing the laser beam. The lens-plate box was mounted in position via a dove tail-wedge arrangement, thus ensuring precise alignment for each hologram. The box was removed for reloading the recording plate and removing exposed holograms.

Holograms were recorded on 4 X 5 inch glass recording plates (Agfa 8E75). The plates were kinematically attached to a brass holder which was in turn held in place by a permanent magnet.

As previously mentioned, two beams were reflected off of the beam splitter into the reference channel. The wedge angle of 1/2 degrees was selected to insure that the beam

reflected off of the back surface would miss the first reference beam mirror. The beam from the front surface of the beam splitter was reflected off of the three reference channel mirrors in the beam splitter box and was directed into the lens plate box. In the lens plate box two more mirrors directed the reference beam such that it was incident to the plate at 30 degrees relative to the hologram.

The holocamera was designed such that the scene-reference beam paths were both spatially and temporally matched. In order to make fine adjustments, the first dielectric scene mirror was mounted on a translating base to compensate for any change in the scene path. All mirrors were mounted on rotating bases and three axis optical mounts to permit independent elevation and azimuthal adjustments.

IV. EXPERIMENTAL METHOD

Three different metallized fuels were tested during the development of the experimental technique: Boron / Magnesium / Teflon DLX / Binder, Boron / Magnesium / Teflon T7A / Binder and B_4C / Magnesium / Binder. All fuels were provided by the Naval Weapons Center.

The HP-9836 computer automatically controlled the operation of the SFRJ after the manual initiation of primary air for the motor. Following the calibration of transducers and setting of gas pressures to achieve desired flow rates, air pre-heat, ignition, run and purge times were input. Gas flow to the vitiated air heater was then manually actuated. After the air heater gases had been ignited and the air heater temperature had risen to 700 F, purge air to the viewing windows was switched on. This was immediately followed by initiation of primary air which provided the SFRJ with air at a pressure, temperature and flow rate typical of the flight environment for this type of ramjet. At a predetermined time the computer would turn the igniters on for a specified period and off again. The motor, if ignition occurred, would sustain until the computer terminated the run with a nitrogen purge.

Since burn times of four seconds were typical, the laser holographic illuminator was fired approximately one second

after the igniters shut down. This was done for two reasons. In the event that there was some delay in firing the laser, a three second margin was available during which the motor continued to sustain. Also,if the motor failed to sustain after the ignition period, some particles might still be present for recording one second after ignition.

For the test firings of the SFRJ, an air mass flux of 0.2 lbm/second with a chamber pressure of approximately 160 psi was selected. The converging nozzle diameter was 0.75 inches.

Following development of the exposed plate, holograms were reconstructed with a krypton-ion laser and viewed through an optical microscope at 2X. The focal plane of the microscope was then traversed through the image created by the reconstruction. Particle sizing was to have been accomplished by comparison with a hologram of the standard Air Force resolution target or through automatic data retrieval and computer image processing.

V. RESULTS AND DISCUSSION

A. HOLOCAMERA DESIGN AND CONSTRUCTION

Design of the holocamera was relatively simple in that it was possible to preserve the optical path lengths used in the AFRPL holocamera. The AFRPL holocamera was able to accomodate a scene volume six inches in length. The length required for the SFRJ scene volume was also six inches, therefore the SFRJ holocamera was designed around the use of the existing AFRPL holocamera lens-plate box. The principle difference in designs arouse from the fact that the AFRPL holocamera reflects light in the horizontal plane while the SFRJ holocamera reflects light in the vertical plane due to the horizontal orientation of the SFRJ.

The camera was designed by first laying out all optical path lengths full scale to ensure accuaracy of dimensioning. Rotating and translating bases were selected for multi-axis gimbaled optical mounts, from commercially avaible sources. These were then layed out beneath the optical paths for sizing and mounting. While the components were the smallest available, in many cases they were still to large to use, and preserve the optical path lengths. Extensive modification of a number of the bases and gimbaled mounts solved the problem. High quality optical mirrors were used for all reflective surfaces. All mirrors were capable of

rotation about three axes and the first mirror in the scene beam channel was capable of translation for matching of optical path lengths. A beam splitter with a 1/2 degree wedge angle was used to split the illuminating beam into scene and reference beam components. An additional mirror was required to reflect the illuminating beam 90 degrees from the horizontal to the vertical plane prior to reaching the beam splitter. A pair of inverting lenses and pinhole arrangement were placed in the scene beam path to reduce scattered light and increase resolution. After laying out all components, an enclosing box was designed around the largest dimensions for mounting and protection of the components. This box was then mounted on three short legs which were drilled and tapped for hex-head bolts. The heads of the bolts were drilled out so that they would fit on ball bearings. The ball bearings were epoxied to nuts which were fixed to a permanent location on the SFRJ test stand. With this arrangment, the camera, when placed on the ball bearings, would always be located in the same place on the test stand and could easily be aligned by manipulation of the three bolts (Figure 5.1).

A cage was designed to receive the lens-plate box from the AFRPL holocamera. The lens-plate box had to be rotated 90 degrees for proper orientation and was fitted with a wedge which mated with the cage to form a dove-tail joint. The wedge was designed to hit a stop which insured that the

lens-plate box was properly aligned. Design and construction of this cage proved to be very difficult and required several iterations before a workable solution was found. Construction of the holocamera required much more time than was originally anticipated due to the extensive milling of components, hand tapping of all screw holes and modifications to the optics mounts. After completion of the box, mounting of the optics was relatively simple.

B. HOLOCAMERA ALIGNMENT

After all of the optical components had been installed, the holocamera had to be aligned. Spatial alignment was accomplished by placing a set of cross-hairs at the entrance to the camera which formed a shadow on the first reflective mirror. All mirrors were adjusted to place the beam in the center of the appropriate mirrors. With the lens-plate box in place, the scene beam and reference beams were incident on the plate holder. The mirrors along both paths were then adjusted as necessary to superimpose the cross-hair shadows of both beams. Temporal alignment was adjusted by translation of the first scene mirror base until resolution was optimized. Little movement was required due to the accuracy with which the optical paths were initially laid out.

C. HOLOCAMERA TESTING

Once the holocamera had been aligned, a test hologram to determine the holocamera resolution limits was required. This was done by using the krypton-ion reconstruction laser as a holographic illuminator and the Air Force standard resoltuion target. The target was placed in the scene volume, and the holographic plate exposed to the illuminator for five seconds. A hologram was obtained with a resolution of 11 microns (Figure 5.2).

D. HOLOCAMERA ALIGNMENT ON THE TEST STAND

The next step was to obtain a hologram of known resolution of the motor combustion volume in a static state. The camera was positioned on the test stand with both SFRJ viewing windows in place (Figure 5.3). The He-Ne alignment laser was then used with the adjustable camera legs to carefully position and align the camera such that the center of the scene beam passed through both windows normal to the SFRJ casing. A fuel slab was placed in the motor to insure that the beam just grazed the fuel surface. Once the holocamera had been correctly positioned, the ball-bearing/nut assemblies were epoxied into place on the test stand. Alignment of all components was very tedious and time-consuming work as the alignment laser was positioned approximately 40 feet from the test stand and was very sensitive to any movement (Figure 5.4). The laser had to be

adjusted for both azimuth and elevation to match that of the holocamera. It was found to be much easier to adjust the position of the windows to match the location of the scene beam, than it was to manipulate the camera and laser. Spatial alignment was then checked using the cross-hair technique. This was also more difficult than anticipated since the He-Ne beam was much less intense than the previously used krypton-ion laser. In order to see the reference beam at all, the test cell had to be completely darkened. With the alignment complete, a resolution target was placed in the scene volume and the pulsed ruby laser used to take a hologram of the SFRJ combustion volume. This hologram was also found to have a resolution of 11 microns (Figure 5.5). With the camera now calibrated on the test stand, the motor was prepared for the first attempt to record a hologram of metallized fuel combustion.

E. SFRJ TEST RUN RESULTS

The motor was loaded with two slabs of Boron / Magnesium / Teflon DLX / Binder fuel. The holocamera was placed in position and aligned. By this point it was clear that the camera was very sensitive to movement and was easily knocked out of alignment. To insure that the camera was properly aligned, a test hologram was made prior to each run. If the hologram was satisfactory, a new plate was placed in the lens-plate box and exposed, but not developed. This plate was then rotated 180 degrees and replaced in the

plate holder. The procedure was used to determine wether or not the camera had malfunctioned in the event that a hologram was not obtained during the SFRJ test. If the first exposure resulted in a hologram, while the second did not, it was assumed that the scene beam was unusable to penetrate the combustion volume with a sufficient intensity to generate a hologram.

The first fuel was burned using an air mass flux of 0.2 lbm/in^2-sec, a nozzle diameter of 0.75 in and a combustor pressure of 135 psia. Air inlet temperature was 1040 R. The motor failed to sustain after igniter shutdown and a hologram was not attempted. Under the assumption that heat loss from the sides of the 2D-SFRJ was too great for combustion to sustain, two strips of black Plexiglas were fixed to the sides of the combustor. The SFRJ was ignited again. With the motor running under ideal conditions the laser firing switch was actuated one second after the igniters switched off, but the laser did not fire. Subsequent investigation found that the laser flash lamp was near failure and was estimated to be good for only five to ten more firings. The lamp was not replaced at this time due to the extensive labor required and the expectation that a hologram would be obtained prior to failure.

Having burned all of the first fuel, the motor was loaded with a fuel of identical composition, except the teflon of the new fuel was T7A rather than DLX. This fuel

was found to be essentially inert. Five attempts were made at a self-sustaining burn, without success. Combustor pressures of 170 psia with air temperatures of 1400 R and ignition times of 5 seconds were insufficient to initiate a self-sustaining burn. It had been thought that use of a high magnesium fuel would provide sufficiently large particles to be seen in the hologram in the event that the boron particles were too small. The initial fuels had been selected because of their magnesium content and the expectation that they would not produce so much smoke that the scene beam would be obscured. However, after the first two test fuels had been consumed, no more of these compositions were available. The only high magnesium fuel available was a Boron Carbide / Magnesium / Binder. While it was known that this fuel would sustain, there was also the chance that it would produce too much smoke for the scene beam to penetrate. All other remaining fuels included T7A teflon, which may have been responsible for the failure of the second fuel to sustain.

The motor was loaded with the fuel and Plexiglas strips to aid in heat retention. The test was conducted with an air mass flux of 0.5 lbm/sec, combustor pressure of 180 psia and a nozzle diameter of 0.75 in. The motor sustained under ideal conditions but the laser failed to fire due to failure of the laser flash lamp. The motor was immediately shut down to conserve fuel.

After replacement of the laser flash lamp, the motor was again run under the same conditions as the previous test and the laser fired one second after igniter shut-down. Subsequent development of the exposed plate however, resulted in an overdeveloped image, which made it difficult to determine whether or not a hologram had been obtained. The SFRJ was run a third time under identical conditions with the laser again firing one second after igniter shut-down. After development of the plate, the reference beam was clearly visible, but the scene beam could not be seen. Attempts to reconstruct the hologram were not successful, indicating that the scene beam had not been able to pass through the combustor with sufficient intensity to generate a hologram. This conclusion was supported by the fact that during the burn, copious amounts of smoke were observed in the motor exhaust. Time constraints precluded any additional tests.

Since holograms of particulates were not obtained, none of the previously discussed data reduction methods was employed.

F. THERMOCOUPLE RESULTS

Satisfactory temperature profiles were obtained by using 0.005 in diameter Chromel-Alumel insulated thermocouple wire. The wire was found to be strong enough to withstand substantial bending, yet small enough to place five

thermocouples within filming range of the high speed motion picture cameras. The thermocouples were spot welded and then sheathed in a stainless steel tube. The tubes were then fed into an Omega multi-conductor high pressure connector which was attached to the motor base. The thermocouples were drawn through the feedthrough, inserted into the bottom fuel slab at pre-drilled depths, and fixed in place with RTV. After the RTV had cured, the fuel was then attached to the motor base. All thermocouple output passed through electronic ice baths mounted on the SFRJ test stand and then into the control room were it was amplified by Pacific amplifiers and fed into an IBM PC/AT. LabTech Notebook software was used for processing and display of the thermocouple data. In all tests, the thermoccuples provided apparently accurate data until regression of the fuel slab exposed the elements to free stream conditions. The thermocouples would usually provided data until burning at approximately 1200 R.

No tests were conducted with the thermocouples while using the HYCAM system.

CONCLUSIONS AND RECOMMENDATIONS

The holocamera designed and constructed for this investigation was very successful in taking holograms of the SFRJ combustor volume under static conditions. Holograms taken had a resolution of 11 microns. Difficulties with associated equipment and fuels resulted in insufficient testing of the holographic technique. It is thought that the technique would be very successful when used with metallized fuels which do not generate so much smoke that the scene beam is obscured. It is recommended that extensive additional testing of fuels be conducted with the techniques developed in this investigation.

The procedure for instrumentation of fuel slabs with thermocouples was quite successful and should be used in conjunction with future studies involving high speed motion pictures.

Recommendations for future work include the use of both holography and automatic data retrieval to obtain particulate data. This could then be compared with data obtained through light scattering techniques. Data should be collected over a range of fuel compositions, air mass fluxes and combustor pressures.

APPENDIX

FIGURES

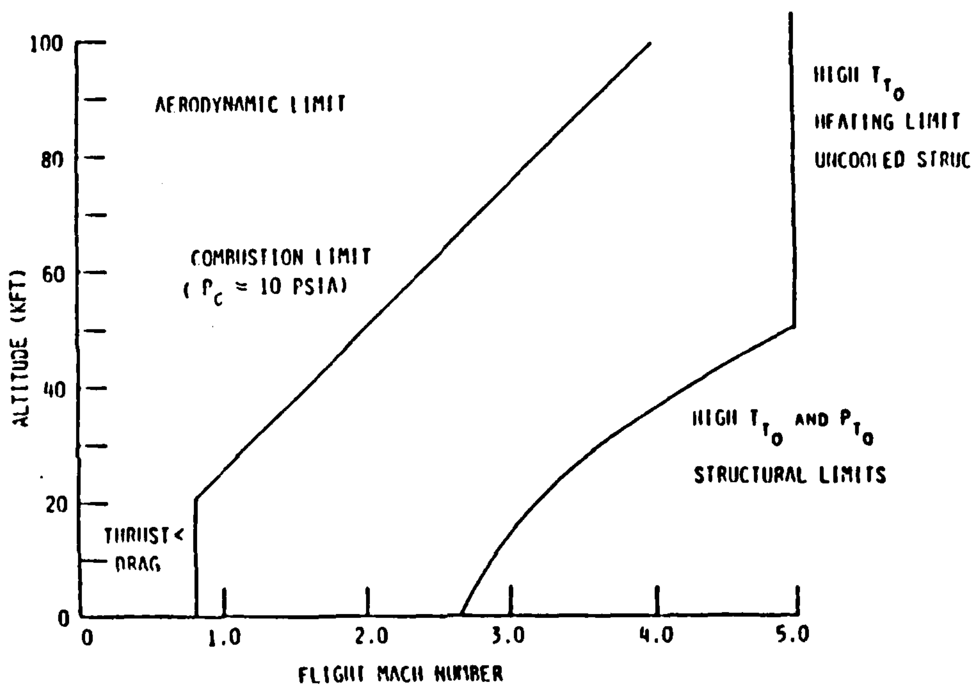

Figure 1.1 Ramjet Operating Envelope [Ref.10]

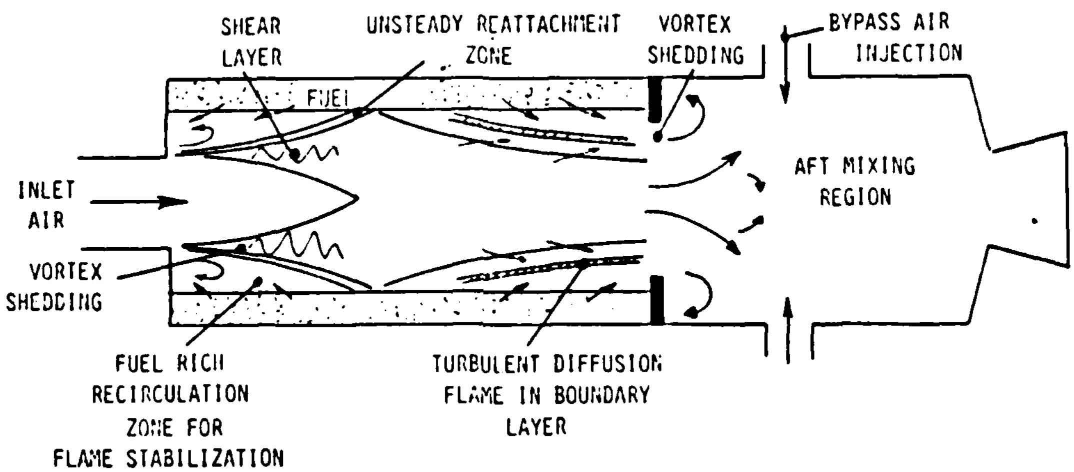

Figure 2.1 Two Dimensional Solid Fuel Ramjet Combustor [Ref. 11]

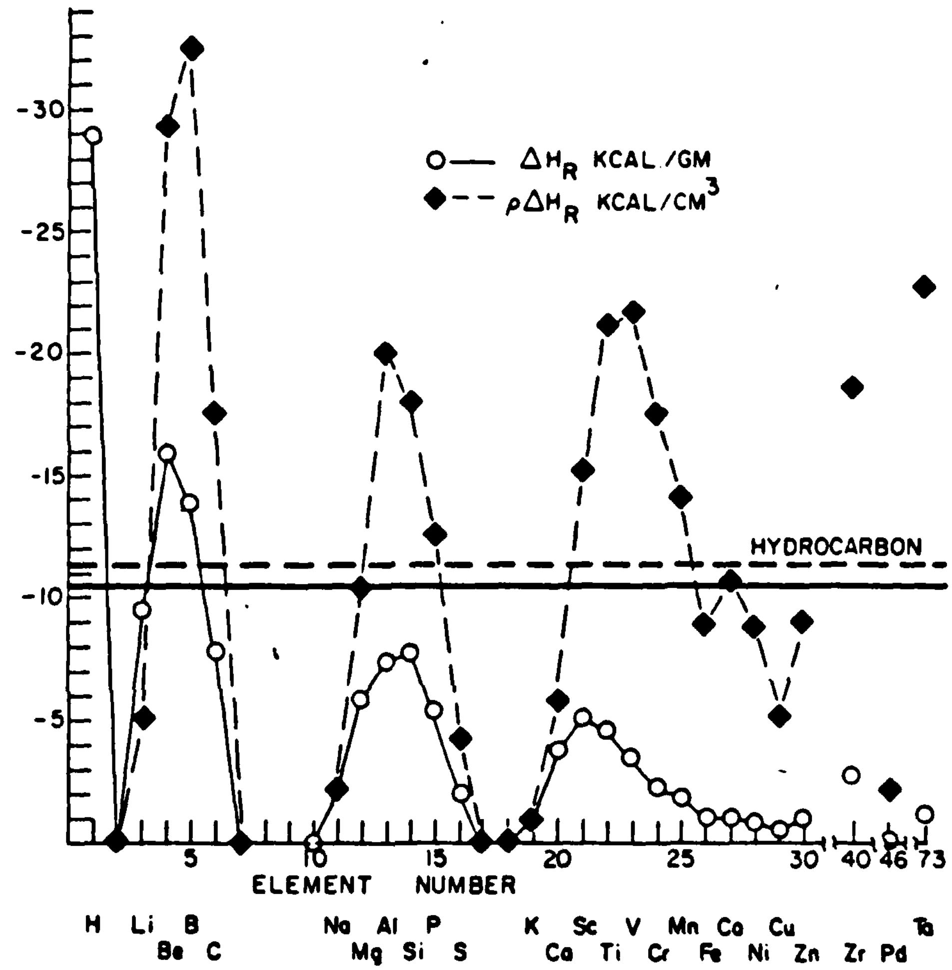

Figure 2.2 Heat of Combustion of Elements per Unit Mass and per Unit Volume Compared with the Values for a Representative Hydrocarbon [Ref. 2]

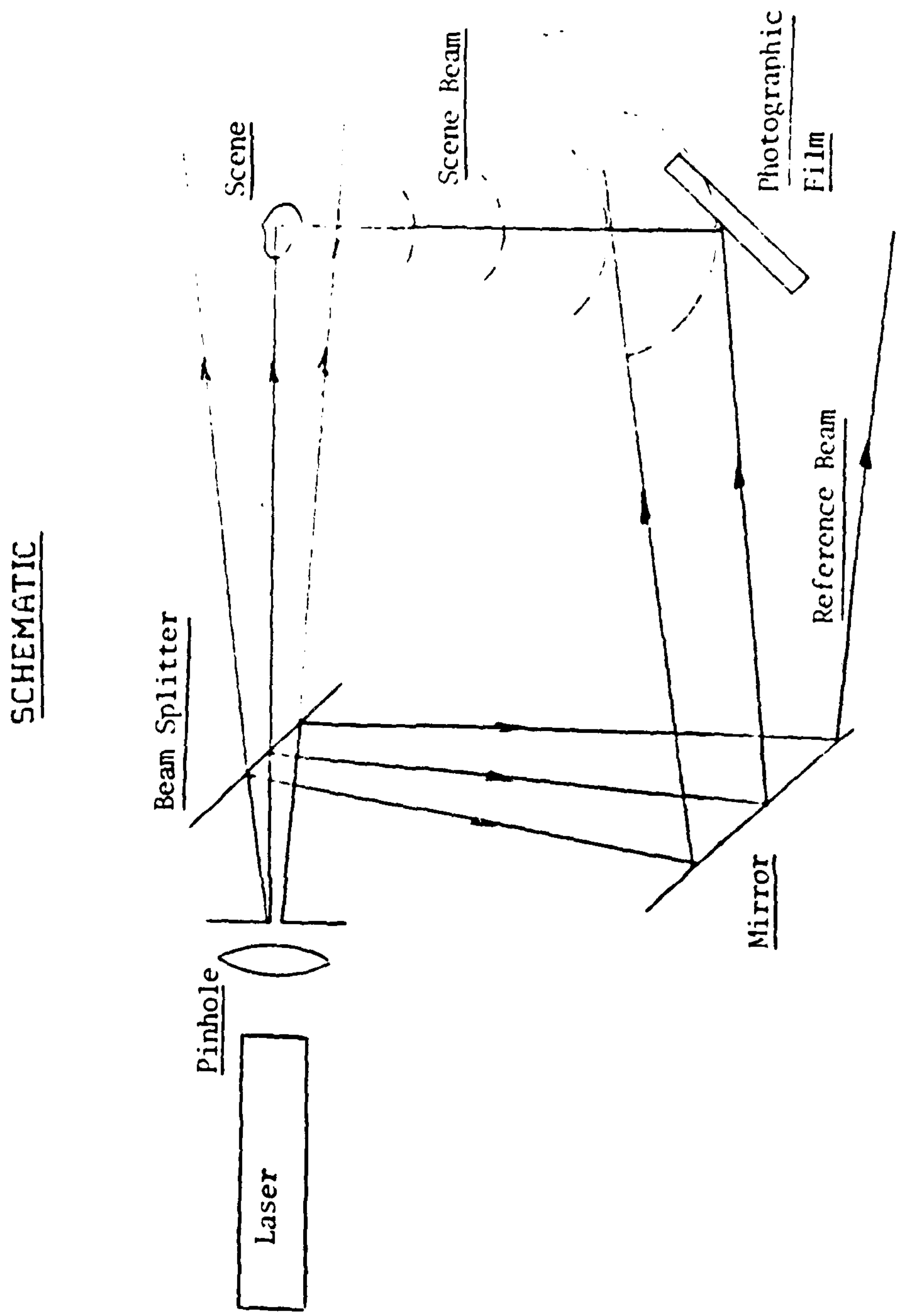

Figure 2.3 Schematic of a Simple Holocamera

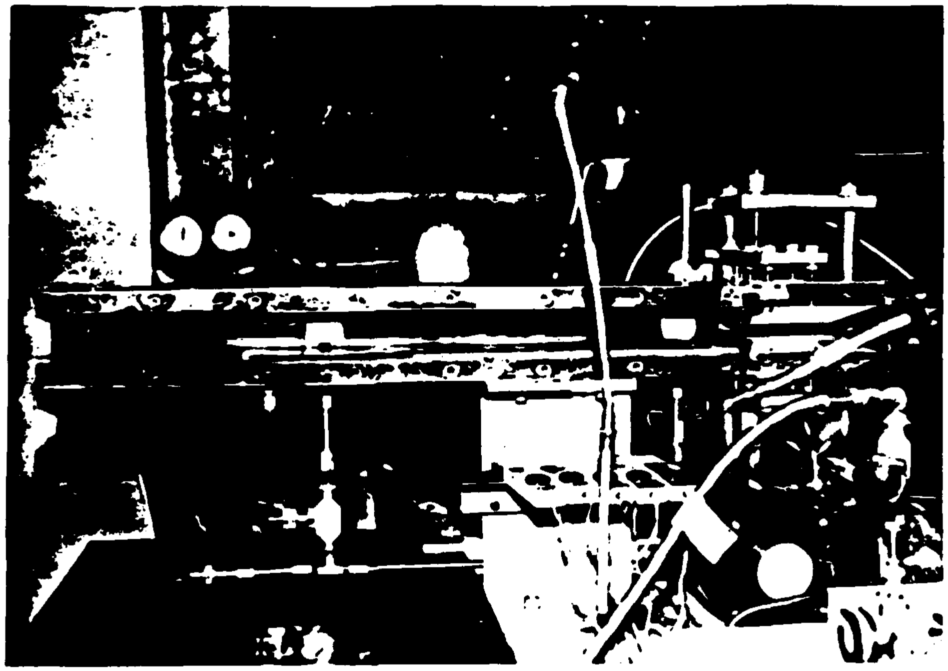

Figure 3.1 Solid Fuel Ramjet Variable Step Height Arrangement

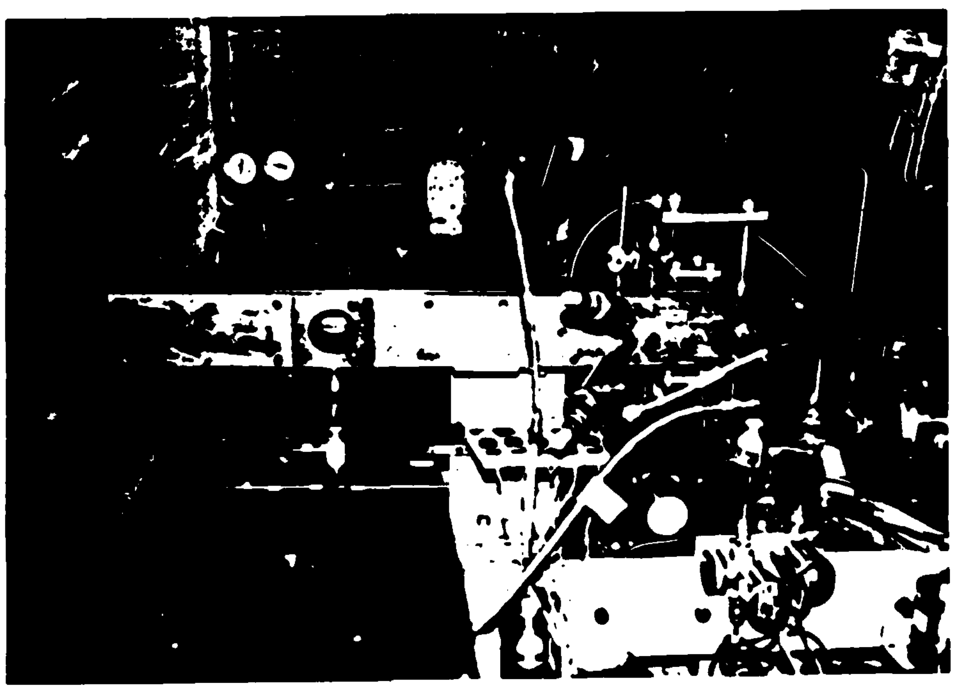

Figure 3.2 Solid Fuel Ramjet Combustion Chamber

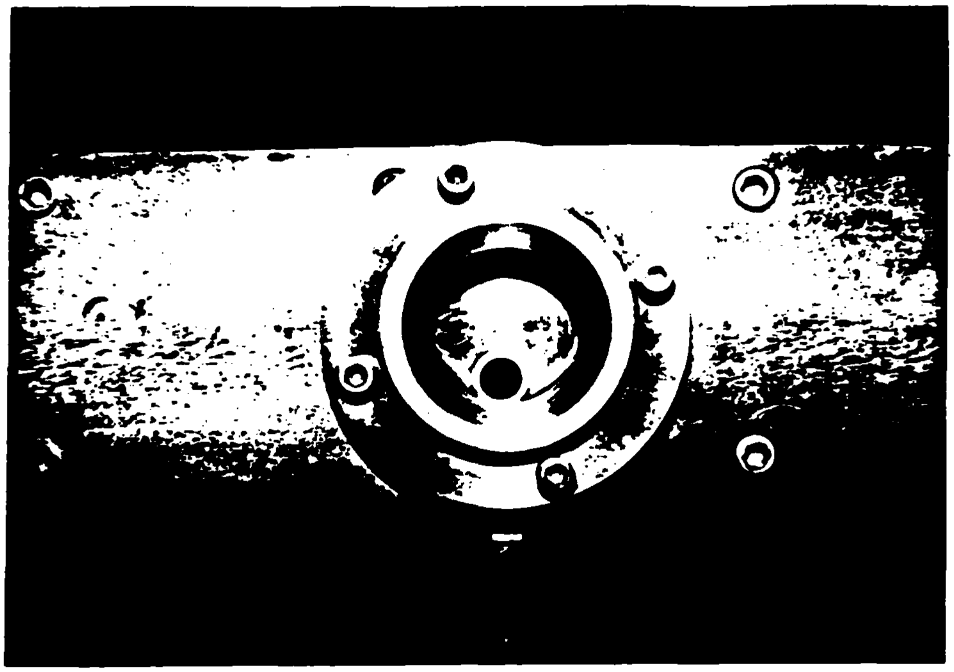

Figure 3.3 Solid Fuel Ramjet Viewing Window

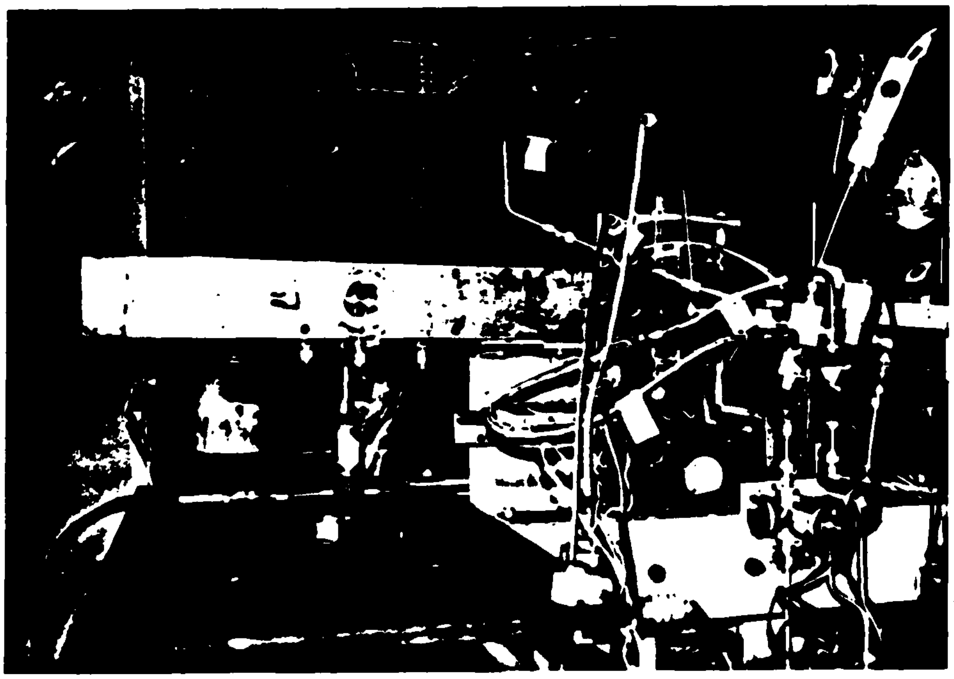

Figure 3.4 Solid Fuel Ramjet Igniters

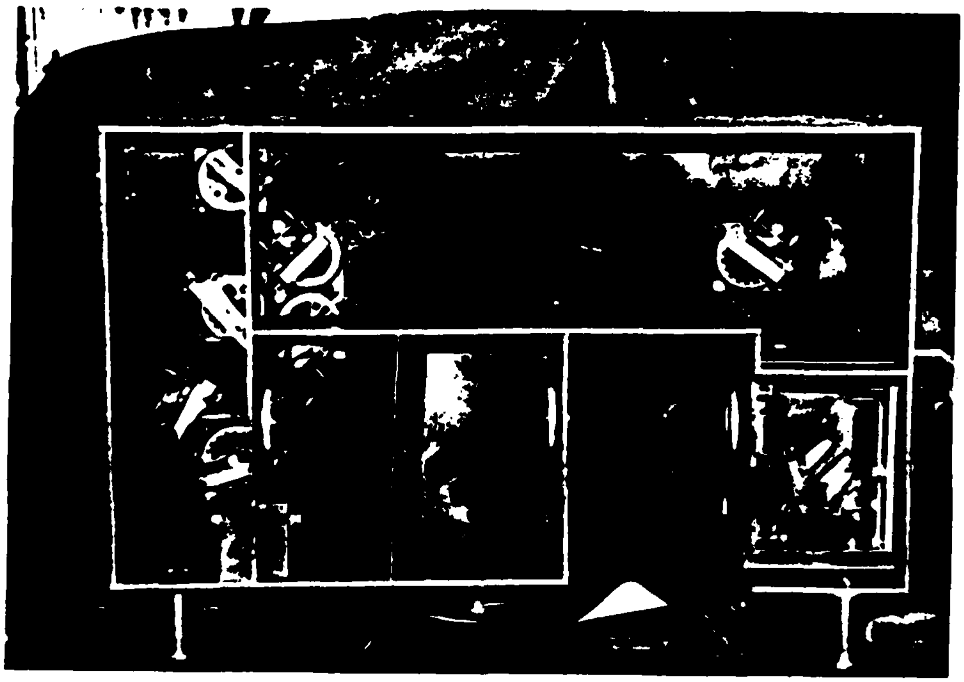

Figure 3.5 Solid Fuel Ramjet Holocamera

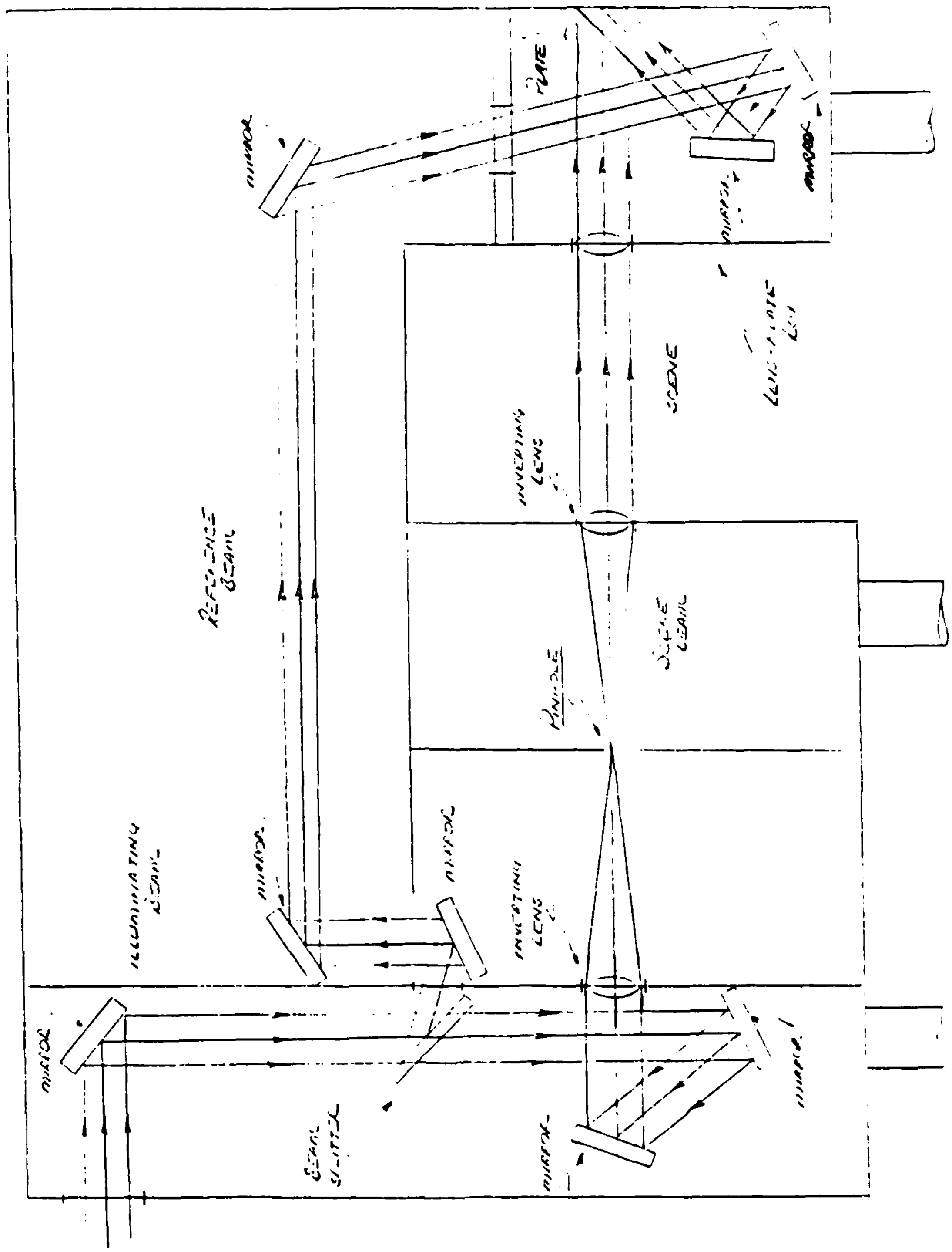

Figure 5.1 Schematic of Solid Fuel Ramjet Holocamera

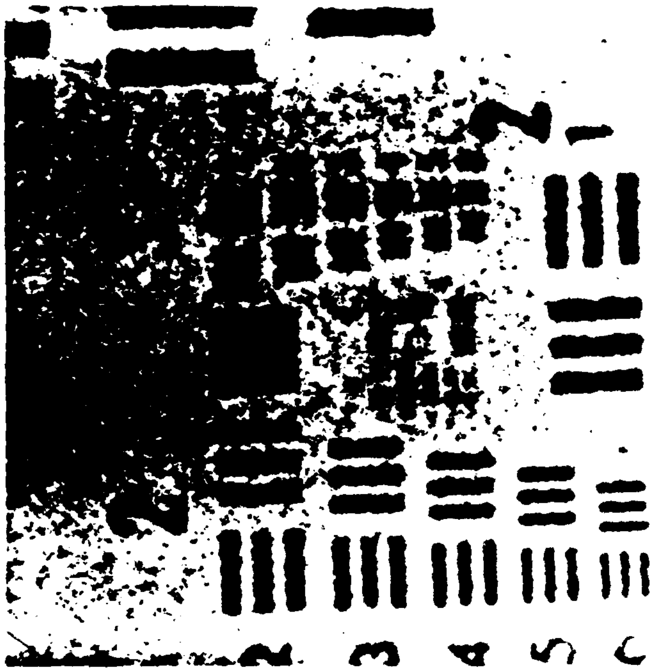

Figure 5.2 Hologram of Air Force standard resolution target using krypton-ion laser

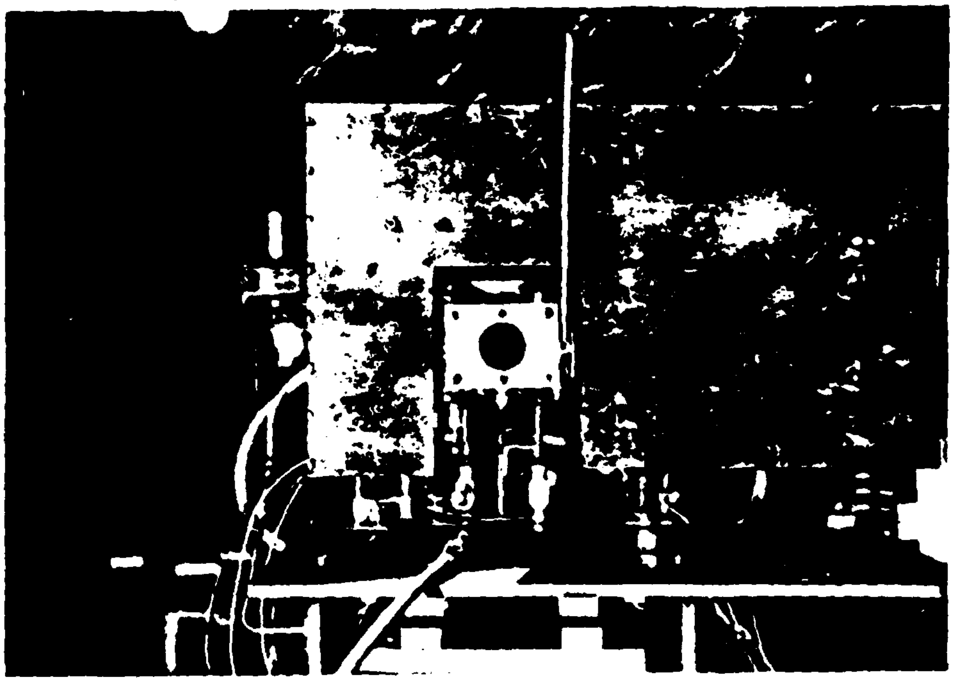

Figure 5.3 Holocamera mounted on Solid Fuel Ramjet Test Stand

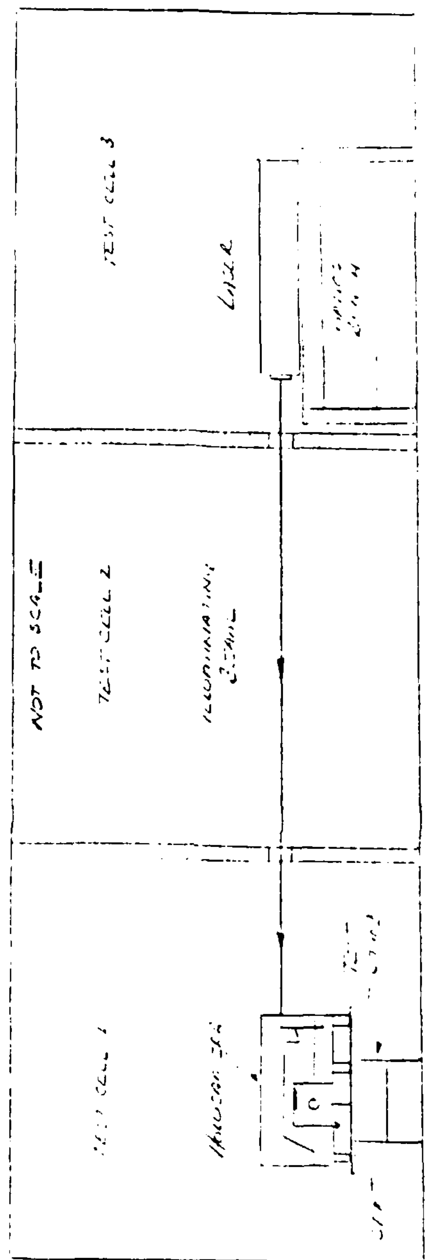

Figure 5.4 Holocamera / SFRJ / Ruby Pulse Laser Arrangement

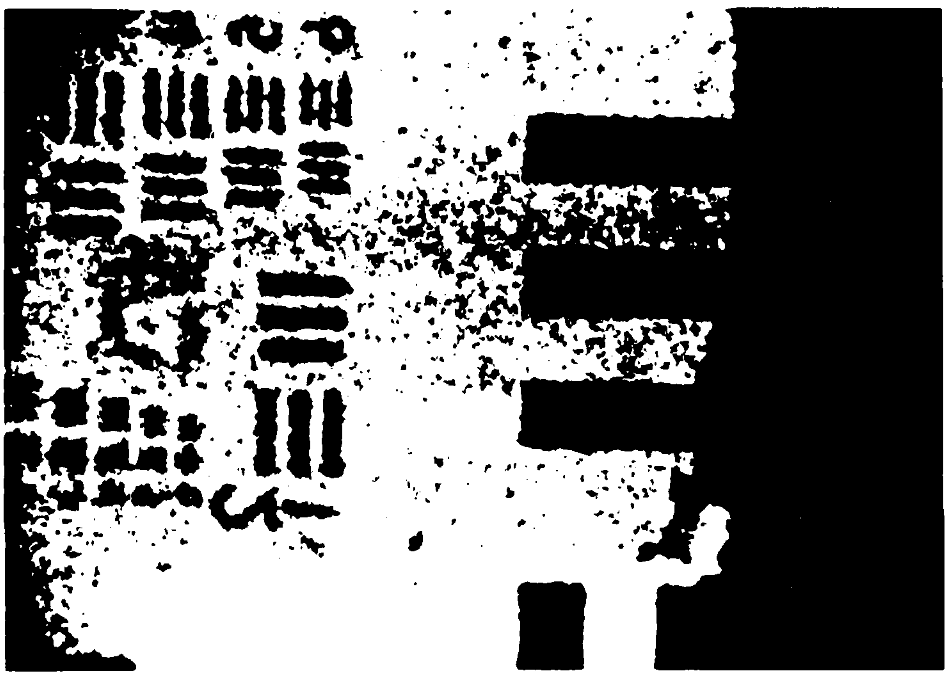

Figure 5.5 Hologram of Air Force standard resolution target inside SFRJ combustor using Ruby Pulse Laser

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